APEX
474

Research and
Development Report

THE RELEASE OF FISSION PRODUCTS FROM REACTOR FUEL

A Literature Survey

P. H. WILKS

GENERAL ELECTRIC
ATOMIC PRODUCTS DIVISION
AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

APEX - 474

C-84 Reactors - Special Features of Aircraft Reactors

C-85 Reactors - Aircraft Nuclear Propulsion Systems

(M-3679, 22nd Edition)
Rev. 1

THE RELEASE OF FISSION PRODUCTS FROM REACTOR FUEL

A Literature Survey

P. H. WILKS

Radiation and Criticality Safety

March 23, 1959

United States Air Force — Contract No. AF 33(600)-38062

United States Atomic Energy Commission — Contract No. AT (11-1)-171

GENERAL ELECTRIC

Atomic Products Division

Aircraft Nuclear Propulsion Department

Cincinnati 15, Ohio

Published by

Technical Publications Sub-Section

DISTRIBUTION

Standard Distribution

1-4	Air Force Ballistic Missile Division
5	AFPR, Boeing, Seattle
6	AFPR, Boeing, Wichita
7	AFPR, Douglas, Long Beach
8-10	AFPR, Douglas, Santa Monica
11-12	AFPR, Lockheed, Marietta
13	AFPR, North American, Canoga Park
14	AFPR, North American, Downey
15-16	Air Force Special Weapons Center
17	Air Materiel Command
18-19	Air Research and Development Command (RDZN)
20	Air Technical Intelligence Center
21-23	ANP Project Office, Convair, Fort Worth
24	Albuquerque Operations Office
25	Argonne National Laboratory
26	Armed Forces Special Weapons Project, Sandia
27	Armed Forces Special Weapons Project, Washington
28-29	Army Ballistic Missile Agency
30	Army Rocket and Guided Missile Agency
31	Assistant Secretary of the Air Force, R & D
32-37	Atomic Energy Commission, Washington
38	Atomics International
39	Battelle Memorial Institute
40-42	Bettis Plant (WAPD)
43	Brookhaven National Laboratory
44	Bureau of Aeronautics
45	Bureau of Aeronautics General Representative
46	BAR, Aerojet-General, Azusa
47	BAR, Chance Vought, Dallas
48	BAR, Convair, San Diego
49	BAR, Grumman Aircraft, Bethpage
50	BAR, Martin, Baltimore
51	Bureau of Yards and Docks
52-53	Chicago Operations Office
54	Chicago Patent Group
55	Curtiss-Wright Corporation
56	Curtiss-Wright, Quehanna
57	Director of Naval Intelligence
58	duPont Company, Aiken
59	Engineer Research and Development Laboratories
60-61	General Electric Company, Richland

62	GE Company, San Jose (AT(30-3)-502)
63	General Nuclear Engineering Corporation
64	Hartford Aircraft Reactors Area Office
65	Idaho Test Division (LAROO)
66-67	Knolls Atomic Power Laboratory
68	Lockland Aircraft Reactors Operations Office
69	Los Alamos Scientific Laboratory
70	Marquardt Aircraft Company
71	Martin Company
72	National Advisory Committee for Aeronautics, Cleveland
73	National Advisory Committee for Aeronautics, Washington
74	National Bureau of Standards
75	Naval Air Development Center
76	Naval Air Material Center
77	Naval Air Turbine Test Station
78	Naval Research Laboratory
79	New York Operations Office
80	Nuclear Development Corporation of America
81	Nuclear Metals, Inc.
82	Oak Ridge Operations Office
83	Office of Naval Research
84	Office of the Chief of Naval Operations
85	Patent Branch, Washington
86-87	Phillips Petroleum Company (NRTS)
88-91	Pratt and Whitney Aircraft Division
92	San Francisco Operations Office
93	Sandia Corporation
94-95	School of Aviation Medicine
96	Sylvania-Corning Nuclear Corporation
97	Technical Research Group
98-105	Union Carbide Nuclear Company (ORNL)
106	USAF Headquarters
107	USAF Project RAND
108	U. S. Naval Radiological Defense Laboratory
109-110	University of California Radiation Laboratory, Livermore
111-122	Wright Air Development Center
123	AFPR North American, Los Angeles
124	Air University Library
125	Assistant Secretary of Defense, R & D (WSEG)
126	BAR, Goodyear Aircraft, Akron
127	Bureau of Ships
128	Jet Propulsion Laboratory
129	Sandia Corporation, Livermore
130-155	Technical Information Service Extension

Special Distribution

156 Dr. M. L. Barad, Geophysics Res. Div., Air Force Cambridge Research Center, Boston, Massachusetts
157 Major Charles M. Barnes, Hq. Det. No. L, ARDC, Wright - Patterson, Ohio
158 Dr. G. V. Beard, Division of Biology and Medicine, AEC, Washington, D. C.
159 Robert S. Brodsky, NRB, Division of Reactor Development, ANPO, Washington, D. C.
160 L. Burris, Argonne National Laboratory, Lemont, Ill.
161 N. R. Chellew, Argonne National Laboratory, Lemont, Ill.
162 Convair, Ft. Worth, Texas, Attention - Dr. B. P. Leonard
163 G. E. Creek, ORNL, Union Carbide Nuclear Co., Oak Ridge, Tenn.
164 R. Carson Dalzell, Chief, Engineering Development Branch, ANPO, Division of Reactor Development, Washington, D. C.
165 H. Feder, Argonne National Laboratory, Lemont, Illinois
166 Lt. Col. W. G. Fisher, ARB, Division of Reactor Development, ANPO Washington, D. C.
167 J. C. Gallimore, Convair - Ft. Worth, Texas
168 Francis Gavigan, Health and Safety, Chicago Operations Office, AEC, Lemont, Illinois
169 A. R. Gilman, Nuclear Metals, Inc., Cambridge, Massachusetts
170 J. W. Healy, G. E. Hanford, Richland, Washington
171 H. G. Hembree, Chief, Reactor Safety Section, Division of Reactor Development - ANPO, Washington 25, D. C.
172 Lt. D. Heti, ARDC, Washington, D. C.
173 R. K. Hilliard, G. E. Hanford, Richland, Washington
174 Mr. John Horan, Idaho AEC, Idaho Falls, Idaho
175 Theodore J. Iltis, NRB, Division of Reactor Development, ANPO, Washington 25, D. C.
176 G. E. Kennedy, MSA Research, Callery, Pennsylvania
177 E. Kinderman, Stanford Research Institute, Palo Alto, California
178 R. C. Koch, Bettis (WAPD), Pittsburgh, Pennsylvania
179 B. Lustman, Bettis (WAPD), Pittsburgh, Pennsylvania
180 J. M. Markowitz, Bettis Plant (WAPD), Pittsburgh, Pennsylvania
181 W. J. Martin, ORNL, Union Carbide Nuclear Co., Oak Ridge, Tennessee
182 J. W. Mausteller, MSA Research Corp., Collery, Pennsylvania
183 William McAllister, Bettis (WAPD), Pittsburgh, Pennsylvania
184 A. O. Mooneyham, Convair, Ft. Worth, Texas
185 Col. M. Morgan, Air Force Special Weapons Center, Kirkland AFB, New Mexico
186 G. W. Parker, ORNL, Union Carbide Nuclear Co., Oak Ridge, Tennessee
187 Capt. Rawers, Air Force Special Weapons Center, Kirkland AFB, New Mexico
188 B. F. Rider, General Electric - Vallecitos, Atomic Power Equipment Dept., San Jose, California
189 S. J. Rodgers, MSA Research, Callery, Pennsylvania
190 J. A. Roll, Bettis (WAPD), Pittsburgh, Pennsylvania
191 Richard Rossi, Reactor Safety and Evaluation, LAROO-USAEC - Lockland
192 A. M. Saul, North American Aviation, Downey, California
193 Calvin Silverstein, Cornell Aeronautical Laboratory, Buffalo 21, New York

Special Distribution

194 Mr. John W. Taylor, U. S. Naval Air Development Center, Aviation Medical Acceleration Laboratory, Johnsville, Pennsylvania
195 Dr. Robert O. Thomas, University of Rochester, Atomic Energy Project, Rochester, New York
196 Dr. Forest Western, Division of Biology and Medicine, U. S. Atomic Energy Commission, Washington 25, D. C.
197 F. J. Witt, Knolls Atomic Power Laboratory, Schenectady, New York

Aircraft Nuclear Propulsion Department

198 R. E. Baker
199 J. T. Bittel
200 V. P. Calkins
201 P. K. Conn
202 A. R. Crocker
203 F. Devens
204 R. C. Evans
205 A. E. Focke
206 D. L. Francis
207 C. C. Gamertsfelder
208 R. F. Gentzler
209 C. R. Gray
210 M. S. Harned
211 R. F. Hoffer
212 G. P. Kerr
213 C. S. Lankton
214 M. C. Leverett
215 S. J. Levine
216 P. E. Lowe
217 F. C. Linn
218 R. F. Lutz
219 R. C. Mann
220 F. W. Mezger
221 S. H. Minnich
222 J. W. Morfitt
223 G. W. Newton
224 R. B. O'Brien
225 W. G. Root
226 D. R. Shoults
227 N. P. Spofford
228 C. L. Storrs
229 F. G. Tabb
230 G. Thornton
231 J. B. Trice
232 J. Van Hoomissen
233 L. D. VanVleck
234 P. H. Wilks
235-241 Library (Idaho)
242-255 Library (Evendale)

ABSTRACT

A discussion of available data on fission product release is presented. The survey is divided into data from actual incidents, field release experiments, laboratory release from fuel element samples, and pyrometallurgy. An author index and an alpha-numerical index are included.

TABLE OF CONTENTS

BLANK

INTRODUCTION

The accidental release of fission products from an operating nuclear reactor represents a potential hazard to those nearby. For this reason, a summary of helpful information on tests, ideas and experience related to fission product release would be of value to persons involved with reactor safety. This survey has been prepared to fill that need, but relevant data are limited. The need for more research in this field is apparent.

It is to the credit of the industry that incidents involving fission product release are few, and much of the available information dealing with large scale release is theoretical in nature. A very limited number of field release experiments has been performed. Laboratory scale experiments have provided some data regarding the fractions of various fission products which are released when fuel or fuel elements are melted, but the applicability of these data toward predicting the seriousness of full scale reactor incidents is open to question.

The following is a survey of the literature which is related to the general problem of fission product release from operating reactors. It is separated into four categories according to the type of information offered by each reference. The categories are as follows: (I) Fission Product Release from Actual Incidents; (II) Field Release Experiments; (III) Laboratory Scale Release from Fuel Element Samples; and (IV) Pyrometallurgy of Spent Uranium Fuel. An alphabetical author index and an alpha-numerical index are also included.

This survey was prepared using the GE-ANPD library card files, Nuclear Science Abstracts, and Abstracts of Classified Reports as primary sources of references. The subject headings which were explored are as follows:

FISSION PRODUCTS

- Escape
- Release

URANIUM

- Fission Products
- Purification

HIGH TEMPERATURE SEPARATION

- Processes
- Pyrometallurgy
- Fuel Elements
- Separation Processes

REACTORS

- Safety
- Disasters

Nuclear Science Abstracts was explored from Volume I to Volume XIII, No. 1. Abstracts of Classified Reports was consulted from Volume I to Volume XV, No. 1. In addition, Chemical Abstracts was investigated from 1950 to 1958 inclusive.

The names of research workers attending a meeting of Fission Product Release Studies at Germantown, Maryland, November 6, 1958 and some of their subordinates were sought in the "Authors" card catalogue. The quarterly reports of their respective facilities were sought in the "Corporate Entries" card catalogue.

In December of 1953 a working party at Harwell, England published plans for a series of fission product release studies. The names of all members of this group were checked in the "Authors" catalogue.

Additional information was obtained through personal communications with C. C. Gamertsfelder and R. E. Baker of Radiation and Criticality Safety, GE-ANP; H. M. Feder and N. R. Chellew of Argonne National Laboratory; G. E. Creek of Oak Ridge National Laboratory; H. G. Hembree, G. V. Beard, and J. Davenport of the AEC, Washington, D. C.; R. C. Brothers of the AEC, Pembroke, Ontario; and J. E. Woolston of Atomic Energy of Canada Limited.

An attempt has been made to restrict the references to those offering data which might conceivably be of value in predicting fission product release caused by overheating in an actual reactor. While the amount of information in this survey is not great, it is felt that the picture of the available data on fission product release which it presents is as complete as is possible at the time of this writing.

BLANK

(I) FISSION PRODUCT RELEASE FROM ACTUAL INCIDENTS

In December of 1952, an excursion occurred at Chalk River, Ontario which resulted in 10,000 curies of long lived fission products being leached by cooling water from damaged fuel elements.[1,2] The contaminated water was confined and very little airborne radioactivity was released from the facility. Approximately eleven percent of the fuel elements were sufficiently overheated to melt and thereby rupture the sheathing. A less serious accident occurred at the NRTS in February, 1957 involving release of fission products to cooling water of the MTR.[3]

The accident at the Windscale No. 1 pile in October of 1957[4,5] resulted in appreciable I^{131} contamination of the countryside and distribution of some locally produced milk was stopped. The reactor released 5×10^4 curies of I^{131}, of which 3×10^4 curies passed through the filtration system and into the atmosphere. Estimates place the total deposition of I^{131} on surrounding vegetation at 2×10^4 curies. The accident caused 3-1/2 tons of uranium to be oxidized while the total iodine release to the filtration system represents that from 2-1/2 tons of uranium.[6] It may be inferred from this that the fractional release of iodine from the affected area was 0.7.

A power excursion in an ANP reactor in November, 1958 resulted in the release of about one tenth percent of the total gross fission products in the reactor.[7] Actual measurements of the amounts of fission products released are presented in Table I.[8] The fuel elements in this reactor were of the metallic

type, having a core of UO_2 in intimate mixture with powdered 80 Ni-20 Cr and clad with 80 Ni-20 Cr.

Table I

Fission Product Release from ANP Excursion, November, 1958

Reactor Inventory-Curies	STACK RELEASE			
	From Stack Monitors		Inferred from Deposition on Vegetation	
	Curies	F	Curies	F
Gross (at 10 min) 4×10^5	400	0.001	---	---
I^{131} (at 0 min) 80	0.16	0.002	0.3	0.004
I^{133} (at 0 min) 480	3.2	0.0067	4	0.0083
I^{135} (at 0 min) 1100	27	0.025	30	0.027
Sr^{91} (at 0 min) 900	0.58	0.0006	1	0.001

(II) FIELD RELEASE EXPERIMENTS

In May, 1958, an experiment was performed at GE-ANPD's Idaho Test Site to determine the effect of burnout of one metallic fuel tube of a high performance air cycle reactor.(9) Burnout was accomplished by reducing the flow of cooling air to the tube. The fractional release of I^{131} ranged from 0 to 0.7 during this experiment, depending on the thermal damage to each portion of the cartridge. Fractional release for the total cartridge was about 0.25.

The Nuclear Aircraft Research Facility, operated by Convair - Fort Worth, has completed a series of fission product release experiments using GE-ANP metallic fuel elements. The fuel samples were heated by induction in graphite crucibles and the distribution of the resulting fallout was studied along with the fractional release of fission products. While analysis of the data is not complete at the time of this writing, descriptions of initial plans and a preliminary discussion of the results are available.(10,11,12)

Chamberlain and McGaw of Harwell have performed field release tests in England using I^{131}, but no details of this work have as yet been made available to the U. S. AEC.(13)

In 1953, a reactor designated as BORAX-1 was intentionally destroyed by completely ejecting a control rod worth 4% K-eff and allowing the fuel to melt.(14) The ensuing reaction between molten fuel and reactor water threw most of the contents of the shield tank into the air. Practically all of the fuel

originally in the reactor was found within a radius of 350 feet around the reactor. Gamma dose rates to the surrounding terrain were quite small even at a distance of less than a mile downwind from the reactor. A detailed report dealing with the health physics aspects of this experiment is available.(15)

(III) LABORATORY SCALE RELEASE FROM FUEL ELEMENT SAMPLES

Parker and Creek of ORNL have contributed most of the available experimental data on fission product release from controlled melting of irradiated fuel specimens. Their data are reproducible but are from very small scale experiments.[16,17] At trace concentrations of fission products, slow melting of APPR type stainless steel plate at 1525°C in air or steam released half of the rare gases, one third of the iodine, one tenth of the cesium and traces of strontium. After 25% burnup the fraction of cesium released increased to 0.6. MTR type aluminum clad samples, containing traces of fission products, released 0.02 of the iodine and 0.10 of the rare gases upon melting at 700°C. Zircaloy type fuel specimens, melted at 1850°C in helium after 15% burnup, released up to 0.95 of the rare gases, 0.6 of the cesium, and 0.80 of the iodine. In air at comparable temperatures the iodine release was reduced to 0.53 and the cesium to 0.05. Strontium release was less than 0.01 in all cases.

Experiments where Parker and Creek employed postage stamp size GE-ANPD metallic fuel specimens have been reported in their latest work.[17] Melted rapidly and cooled immediately, they released 0.10 of the xenon, 0.04 of the iodine, traces of cesium and strontium. Another specimen, kept at a temperature above the melting point for four hours, oxidized completely and released 0.77 of the xenon and krypton, 0.99 of the iodine, 0.016 of the cesium and a trace of strontium. The investigators themselves question the validity of the iodine value of 0.99, there being evidence that it is actually closer to 0.77.[18] Parker, Creek, and Martin have recently performed some experiments with UO_2 type fuel. Their preliminary data indicate oxides to be inherently retentive, since it was found

that release of volatile fission products at 1600°C is considerably less than would be expected from metallic fuel. In two experiments, rare gas release fractions of 0.01 and 0.013 were obtained.

Lustman and others[19,20] have studied the evolution of rare gases from irradiated UO_2 in terms of diffusion coefficients. Although there is a good deal of scatter in the data, the importance of both porosity and temperature is clear from these studies.

Some experiments have been performed on fission product release from GE-ANPD tubular metallic and ceramic fuel element specimens. The data from these tests, performed in the LITR reactor at Oak Ridge and the MTR in Idaho, are very difficult to analyze. However, some results are available.[21,22,23,24,25,26] The data are presented in terms of release rate, defined as the percent of nuclei formed which escape to the cooling air stream. With few exceptions release rates were less than 0.1 percent. For metallic samples the most important factors controlling release rate of iodine seem to be integrity of the cladding and temperature. Comparison of data from ceramic elements showed that an increase in temperature of 300°F increased iodine release by a factor of twenty. As might be expected, the porosity of ceramic specimens is another very important factor. Some data have been obtained from coated ceramic samples, but the results are inconclusive at present.

Data were obtained at MSA Research[27] by melting Zircaloy clad PWR type elements at 1650°C in a steam atmosphere. The assemblies, which contained only

trace amounts of fission products, lost about half of the xenon and from 0.01 to 0.26 of the iodine. Iodine release was greater during slow meltdown, where 8 minutes were required to melt the element vs. 4 minutes for fast meltdown.

Hilliard of GE-Hanford Atomic Products Operation has recently published a paper on oxidation of Uranium.[28] This work was performed in preparation for future research on fission product release.

BLANK

(IV) PYROMETALLURGY OF SPENT URANIUM FUEL

Much work has been done on the purification of irradiated fuel by melting the fuel under various conditions. Since under these conditions volatile fission products escape, this work is somewhat applicable to the problem at hand.

Historical background for pyrometallurgical purification is presented in a literature survey by E. S. Bomar.[29] A bibliography on the effect of heating irradiated uranium has been compiled by Hilliard.[30]

In the laboratory, Whitman[31] has performed experiments in zone melting in an attempt to remove fission products from uranium, and Gilman[32] removed essentially all the xenon by transient heating of the fuel. Saul[33] heated small (2-4g) surface oxidized fragments of irradiated uranium which had been cooled 3 years to 1275-1400°C. At 1275°C 1/2 of the rare earths and 1/3 of the strontium and cesium migrated to the oxide. At 1400°C 2/3 of the rare earths, 1/2 of the cesium, 1/3 of the strontium and small amounts of plutonium were removed.

Feder and Chellew, however, have gathered the data which are of greatest general interest.[34,35] Their procedure involves induction heating of "Fissium" (an alloy of uranium with small amounts of molybdenum, ruthenium, zirconium, etc., which is intended to represent spent uranium fuel). Non-radioactive xenon and iodine are added in the proper amounts when it is wished to study the release of these and the addition of irradiated uranium pins furnishes tracer quantities

of radioactive fission products to indicate the distribution of the non-radioactive atoms.

The following general conclusions can be drawn from the pyrometallurgical data, although their significance with regard to reactor incidents is subject to question.

A very important factor in the fractional release of rare gases is their initial concentration. When concentrations are on the order of 0.01 ppm, escape of xenon takes place by a slow diffusion process. Diffusion is the mechanism of release even at 1300°C, 200°C above the melting point of fissium. However, when concentrations approach those that would be expected in spent fuel (200 ppm), essentially all the xenon is released just above the melting point of 1100°C.

Feder and Chellew have shown that the fraction of iodine released is more dependent on temperature than on concentration. In experiments at 1300°C, one third to one half of the iodine was released over a three hour period in each case even where concentrations were as far apart as 0.008 ppm and 415 ppm. At 1400°C, however, 0.85 of the iodine was released in 2-3 hours from samples containing 3.5 and 200 ppm of iodine. The iodine that had been added was shown to have reacted with metallic uranium to form UI_3.[36] The stability and non-volatility of this compound is thought to have kept to a minimum the dependence of fractional release on initial concentration.

NUMBERED REFERENCES BY TYPE OF DATA

(I) FISSION PRODUCT RELEASE FROM ACTUAL INCIDENTS

1. Lewis, W. B., "The Accident to the NRX Reactor on December 12, 1952." TID-2011 (p. 9-19). The incident is described. Secret - R. D. Unclassified copy available as DR-32.

2. Hurst, D. G., "The Accident of the NRX Reactor - Part II." GPI-14. Reactor damage is described. Unclassified.

3. Witt, F. J., "Fission Product Release from KAPL-30 Fuel Element Failure." KAPL-M-SMS-72, written 1957. NSA 11:12236. Review of MTR incident involving release of fission products to cooling water. Unclassified.

4. Himsworth, H. P., "Accident at Windscale No. 1 Pile on 10th October, 1957." Her Majesty's Stationery Office, London, November, 1957. The accident is described. Unclassified.

5. Dunster, H. J., Howells, H., and Templeton, W. L., "District Surveys Following the Windscale Incident, October, 1957." A/CONF.15/P/316, 1958. Unclassified.

6. Beard, G. V., private communication.

7. General Electric Company - Aircraft Nuclear Propulsion Department, "Engineering Progress Report APEX-30." December, 1958. Pages 48-60 describe the excursion. Secret - R. D.

8. Gamertsfelder, C. C., private communication.

(II) FIELD RELEASE EXPERIMENTS

9. Baker, R. E., Gamertsfelder, C. C., and Gentzler, R. F., "Final Report First Meltdown Experiment (Operation BOOT)." APEX-445, January, 1959. A description of the experiment and analysis of the data. Secret - R. D.

10. Mooneyham, A. O., Convair - Fort Worth, FZM-1109, "Presentation on Fission Product Dispersal Experiment Plans." April, 1958. A description of plans for fission product release tests at ITS during the summer of 1958. Unclassified.

11. Convair - Fort Worth, "Fission Product Field Release Tests - Experiment Design." FZM-1707, June, 1958. A description of the design of tests proposed in FZM-1109. A total of twelve releases are planned, half employing fuel elements which are aged after irradiation and half employing freshly irradiated fuel elements. Each melt of freshly irradiated elements is expected to release about 30 curies of I^{131}. Each aged element is expected to release less than one curie of C_s-137 and Kr-85 combined. Unclassified.

12. Nuclear Aircraft Research Facility, "NARF Progress Report." June through November, 1958. NARF-58-54P, p.p. 71-79. Nine of the twelve releases described in FZM-1707 were executed. Some data for cloud dose are presented. Confidential.

13. Davenport, J., AEC, Washington, D. C., private communication.

14. Dietrich, J. R., "Experimental Determinations of the Self Regulation and Safety of Operating Water Moderated Reactors." P/481 Peaceful Uses of Atomic Energy, Vol. 13, United Nations, New York, 1956. Unclassified.

15. Griffiths, P., Sill, C. W., and Wilhelmsen, M., "Health Physics Aspects of the BORAX Experiment of July 22, 1954, at the National Reactor Testing Station." IDO-12002. Secret - R. D.

(III) LABORATORY SCALE RELEASE FROM FUEL ELEMENT SAMPLES

16. Parker, G. W. and Creek, G. E., "Experiments on the Release of Fission Products from Molten Reactor Fuels." CF-57-6-87, November, 1957. Unclassified.

17. Creek, G. E., Martin, W. J., and Parker, G. W., "Experiments on the Release of Fission Products from Molten Reactor Fuels." ORNL-2616. Contains new data which were not presented in CF-57-6-87. Unclassified.

18. Baker, R. E., private communication.

19. Lustman, B., "Release of Fission Gases from UO_2." WAPD-173, March, 1957. Unclassified.

20. Markowitz, J. M., Koch, R. C., and Roll, J. A., "Release of Fission Gases from Irradiated Uranium Dioxide." WAPD-180, July, 1957. Unclassified.

21. Conn, P. K., Unpublished, "Comparison of Radiochemical Data from Insert 2-B." A discussion of the reliability of data on fission product release during Insert 2-B test. No hazards considerations.

22. Trice, J. B., Unpublished, "Preliminary Evaluation of Insert 2-B Fission Product Release Data." A letter to V. P. Calkins summarizing the total picture of fission product release from this test.

23. Conn, P. K., "Fuel Element Test LTC-14." Unpublished. A full description of the test. Release rates for I^{131}, Ba^{140}, and Sr^{89} are given.

24. Conn, P. K., "Fission Product Release Measurements of Tests LTC-17, 18, and 19." Unpublished. Tabulated data from experiments with three different types of ceramic fuel elements.

25. Bittel, J. T., and Conn, P. K., "Metallographic Studies of Fueled Tubes." Unpublished. A memorandum discussing LTC-19 in greater detail.

26. Conn, P. K., "Summary of Fission Product Release Data from GE-ANPD." Unpublished. Includes data from all previous tests.

27. Rodgers, S. J., and Kennedy, G. E., "Fission Product Release During a Simulated Meltdown of a PWR Type Core." NS-200-021, October, 1958. Unclassified.

28. Hilliard, R. K., "Oxidation of Uranium in Air at High Temperatures." HW-58022, December, 1958. Unclassified.

(IV) PYROMETALLURGY OF SPENT URANIUM FUEL

29. Bomar, E. S., CF 54-11-26, "Literature Survey of Pyrometallurgical and Recovery Processes." November, 1954. Rather obsolete but discusses historical background for work on volatilization of fission products pointing out the inconsistencies in the results. Confidential - R. D.

30. Hilliard, R. K., "Effect of Heating Irradiated Uranium." HW-52753, November, 1957. Abstracts of 70 documents pertaining to the effects of heating irradiated Uranium as a preliminary to laboratory investigation of fission product release in possible Hanford reactor disaster. A literature search, not exhaustive but biased toward Hanford applicability. Secret - R. D.

31. Whitman, C. I., SEP-179, "Zone Melting of Uranium." June, 1955. Migration is observed but no release of fission products. Unclassified.

32. Gilman, A. R., "Removal of Fission Product Gases by Transient Melting." NMI-1167, May, 1957. Essentially all Xenon was removed from pin-type fuel elements in a short time. Unclassified.

33. Saul, A. M., NAA-SR-1361, "The Removal of Fission Products from Molten Irradiated Uranium by Solid Oxides." September, 1955. Unclassified.

34. Feder, H. M., Argonne National Laboratory Chemical Engineering Summary Reports, first and second quarters of 1958, ANL-5858 and ANL-5896. Confidential-R. D.

35. Burris, L., Chellew, N. R., Feder, H. M., et al. "Developments in Melt Refining of Reactor Fuels." A/CONF 15/P/538, 1958. A summary of work done at ANL. Behavior of some elements is discussed. Unclassified.

36. Chellew, N. R., private communication.

AUTHOR INDEX

Lewis, W. B., ref. 1.

Lustman, B., ref. 19.

Markowitz, J. M., ref. 20.

Martin, W. J., ref. 17.

Mooneyham, A. O., ref. 10.

Nuclear Aircraft Research Facility, ref. 12.

Parker, G. W., ref. 16, 17.

Rodgers, S. J., ref. 27.

Roll, J. A., ref. 20.

Saul, A. M., ref. 33.

Sill, C. W., ref. 15.

Templeton, W. L., ref. 5.

Trice, J. B., ref. 22.

Whitman, C. I., ref. 31.

Wilhelmsen, M., ref. 15.

Witt, F. J., ref. 3.

ALPHA-NUMERICAL INDEX

A/CONF 15/P/316 (1958) Dunster, H. J., Howells, H., and Templeton, W. L., District Surveys Following the Windscale Incident. Unclassified.

A/CONF 15/P/538 (1958) Burris, L., Chellew, N. R., Feder, H. M., et al., Developments in Melt Refining of Reactor Fuels. Unclassified.

ANL-5858 Feder, H. M., Argonne National Laboratory Chemical Engineering Summary Report, first quarter - 1958. Confidential - R. D.

ANL-5896 Feder, H. M., Argonne National Laboratory Chemical Engineering Summary Report, second quarter - 1958. Confidential - R. D.

APEX-30 General Electric Company Aircraft Nuclear Propulsion Department, Engineering Progress Report, December - 1958. Secret - R. D.

APEX-445 Baker, R. E., Gamertsfelder, C. C., and Gentzler, R. F., Final Report First Meltdown Experiment (Operation BOOT). Secret - R. D.

CF 54-11-26 Bomar, E. S., Literature Survey of Pyrometallurgical and Recovery Processes. Confidential - R. D.

CF 57-6-87 Parker, G. W., and Creek, G. E., Experiments on the Release of Fission Products from Molten Reactor Fuels. Unclassified.

DR-32 Lewis, W. B., included in TID-2011 (p. 9-19). Unclassified.

FZM-1109 Mooneyham, A. O., Presentation of Fission Product Dispersal Experiment Plans. Unclassified.

FZM-1707 Convair - Fort Worth, Fission Product Field Release Tests - Experimental Design. Unclassified.

GPI-14 Hurst, D. G., The Accident of the NRX Reactor - Part 11. Unclassified.

HW-52753 Hilliard, R. K., Effect of Heating Irradiated Uranium. Secret - R. D.

HW-58022 Hilliard, R. K., Oxidation of Uranium in Air at High Temperatures. Unclassified.

IDO-12002 Griffiths, P., Sill, C. W., and Wilhelmsen, M., Health Physics Aspects of the BORAX Experiment of July 22, 1954, at the National Reactor Testing Station. Secret - R. D.

KAPL-M-SMS-72 Witt, F. J., Fission Product Release from KAPL-30 Fuel Element Failure. Unclassified.

NAA-SR-1361 Saul, A. M., The Removal of Fission Products from Molten Irradiated Uranium by Solid Oxides. Unclassified.

NARF-58-54P National Aircraft Research Facility, NARF Progress Report - June through November, 1958. Confidential.

NMI-1167 Gilman, A. R., Removal of Fission Product Gases by Transient Melting. Unclassified.

NS-200-021 Rodgers, S. J., and Kennedy, G. E., Fission Product Release During a Simulated Meltdown of a PWR Type Core. Unclassified.

ORNL-2616 Parker, G. W., and Creek, G. E., Experiments on the Release of Fission Products from Molten Reactor Fuels. Unclassified.

SEP-179 Whitman, C. I., Zone Melting of Uranium. Unclassified.

TID-2011 Lewis, W. B., The Accident to the NRX Reactor on December 12, 1952. (Also available as DR-32). Secret - R. D.

WAPD-173 Lustman, B., Release of Fission Gases from UO_2. Unclassified.

WAPD-180 Markowitz, J. M., Koch, R. C., and Roll, J. A., Release of Fission Gases from Irradiated Uranium Dioxide. Unclassified.